Cluster Cosmology and Projection Effects: Validating a Robust Pipeline and Application to SDSS Data

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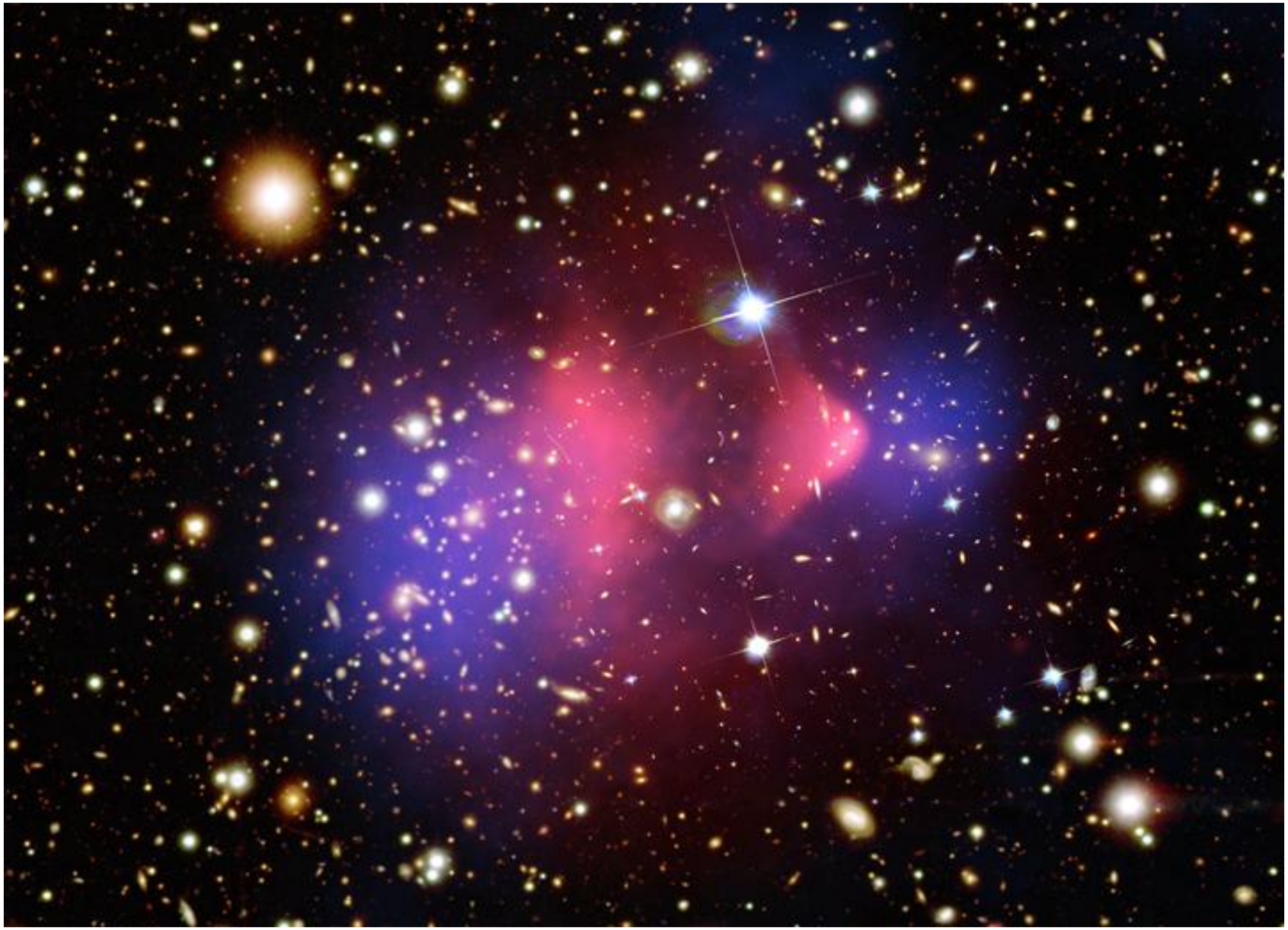
Galaxy Clusters as Cosmological Probes



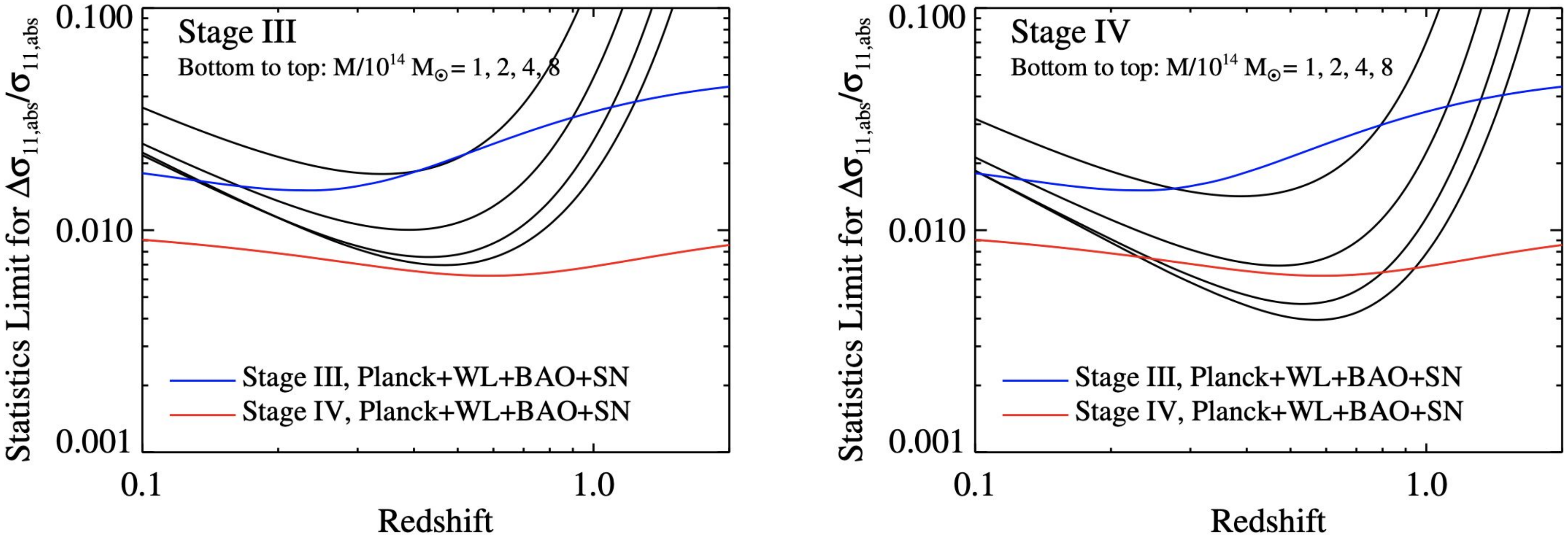
X-ray: NASA/CXC/CfA/ M. Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

Long history of helping us prove important things...

Galaxy Clusters as Cosmological Probes

- **Clusters make great cosmological probes!**
- **Sensitive to background cosmology**
  - Background evolution controls the evolution of the volume element
  - Impacts both the current number density as well as the relative evolution of number density over cosmic history
  - In ΛCDM, controlled by the matter density parameter Ω_m
- **Sensitive to perturbations**
  - σ_8: variance (“clumpiness”) of density perturbations
  - Clusters form from the highest density peaks in the initial density field
  - Higher $\sigma_8 \rightarrow$ more high-density peaks $\rightarrow$ more clusters

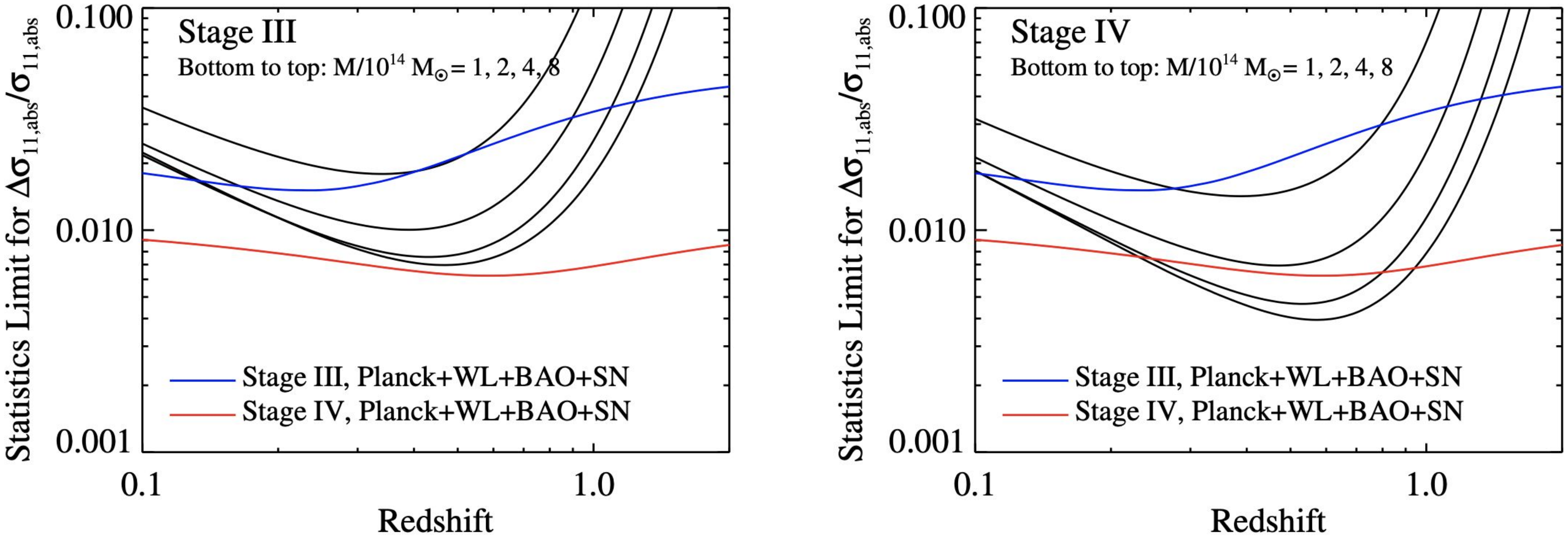
The “Promise”



Snowmass ‘13, Huterer et al.

“ We see that galaxy clusters are statistically competitive with and often better than probes

The "Promise"



Snowmass '13, Huterer et al.

" We see that galaxy clusters are statistically competitive with and often better than probes

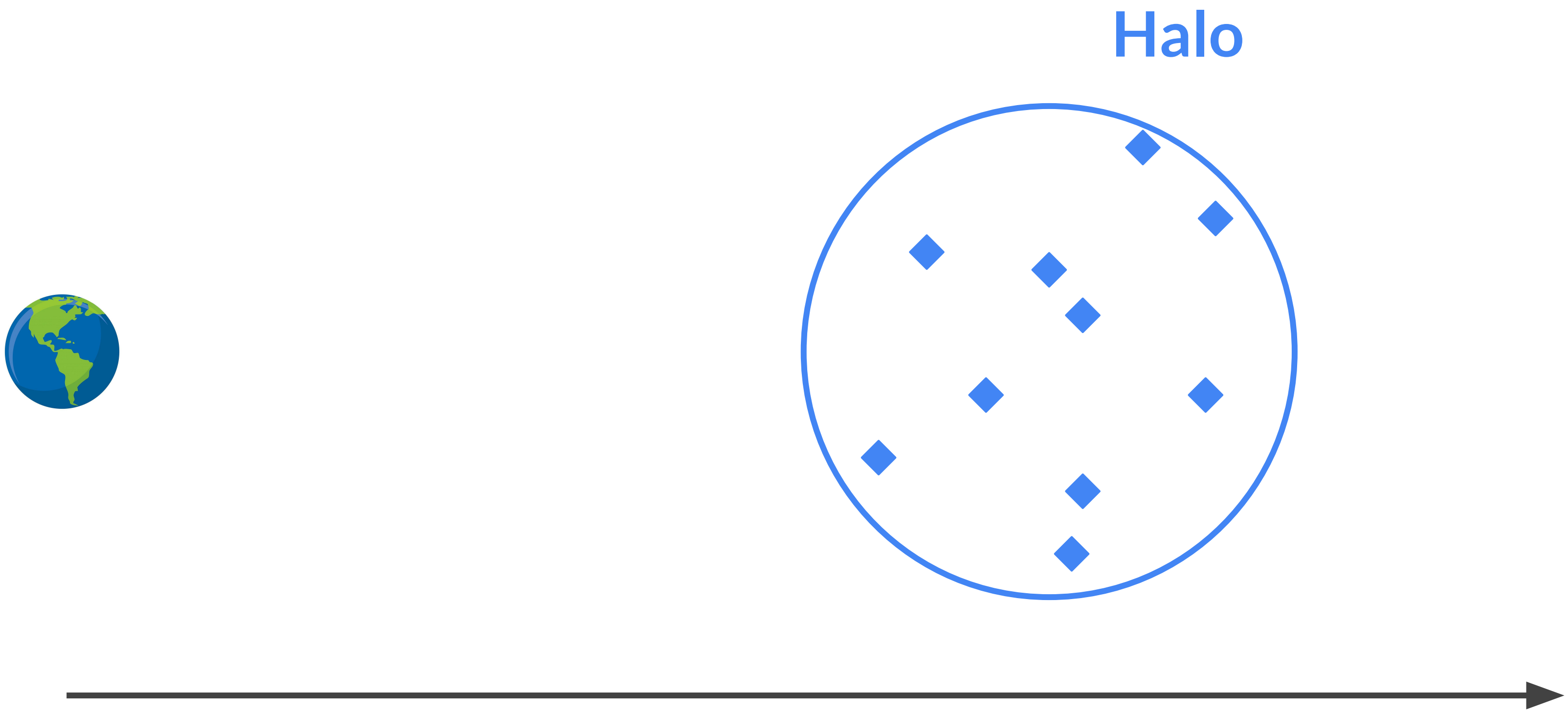
[...] the cosmological utility of cluster samples is always limited by our ability to estimate the corresponding cluster masses."

Optical Clusters

- **Operates based on photometric galaxy surveys**
- **Upsides**
  - Relatively easy to identify uniformly and completely
  - Relatively easy to obtain large sample sizes
  - Self-consistent mass calibration becomes possible via lensing masses
- **Downsides**
  - Photometry (and photometric redshifts) is inherently noisy;
    much of the line-of-sight information is lost
  - Results are highly dependent on the cluster finder algorithm

Projection Effects

- **The line-of-sight issue**



Projection Effects

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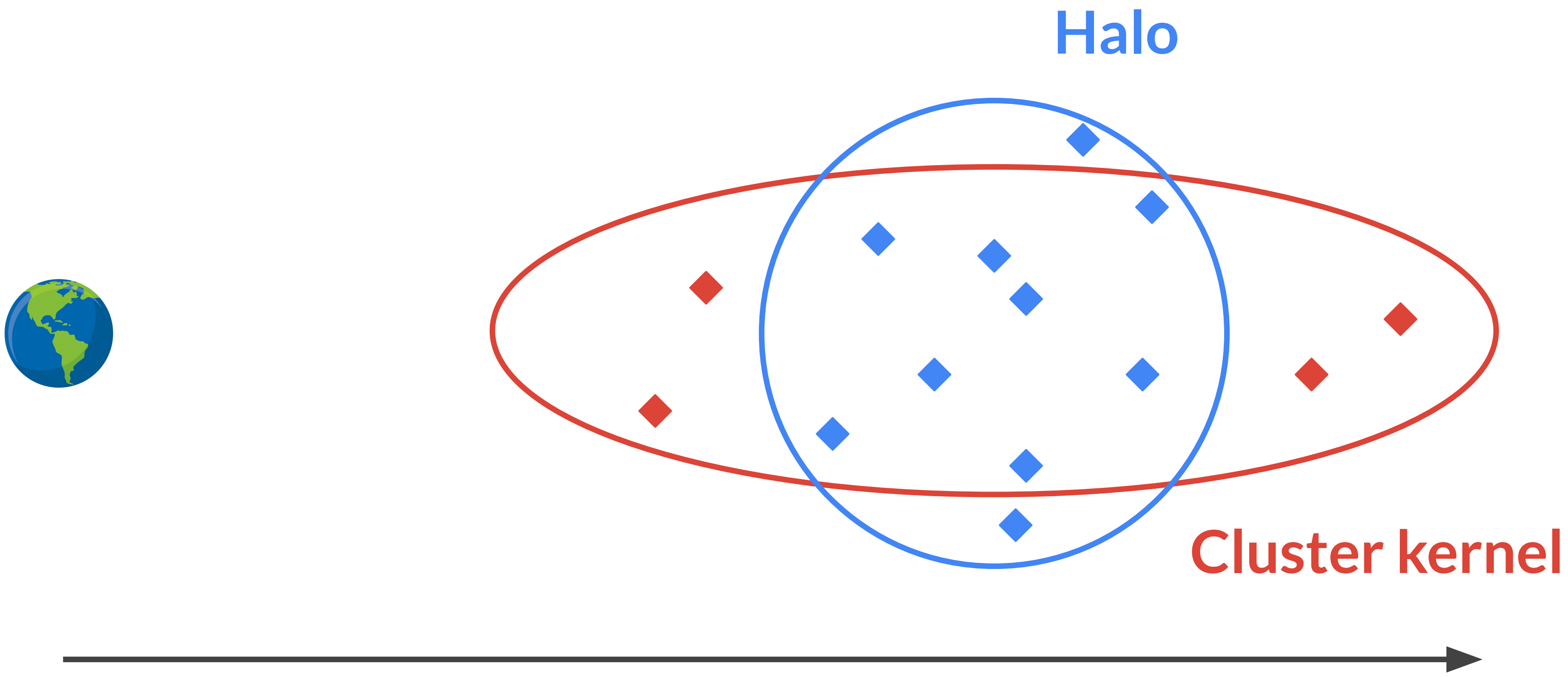

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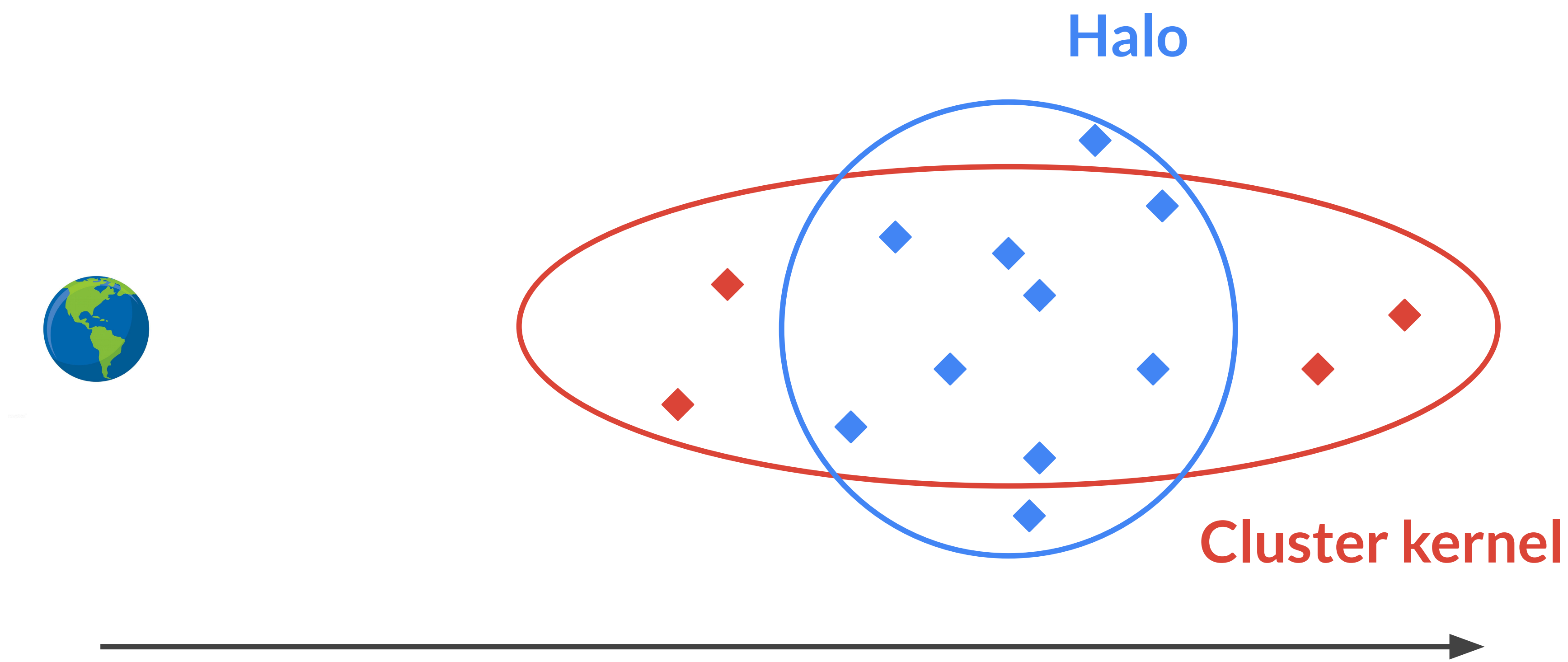
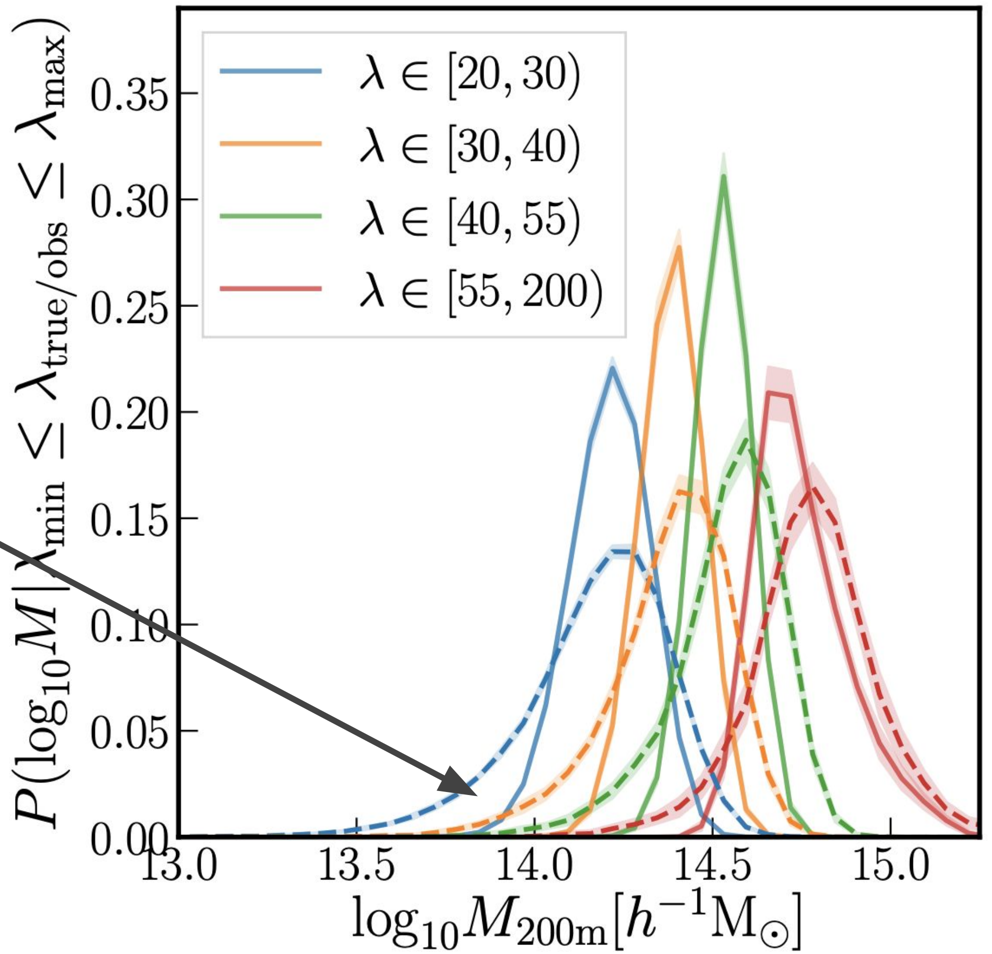


Interlopers contaminate the true richness

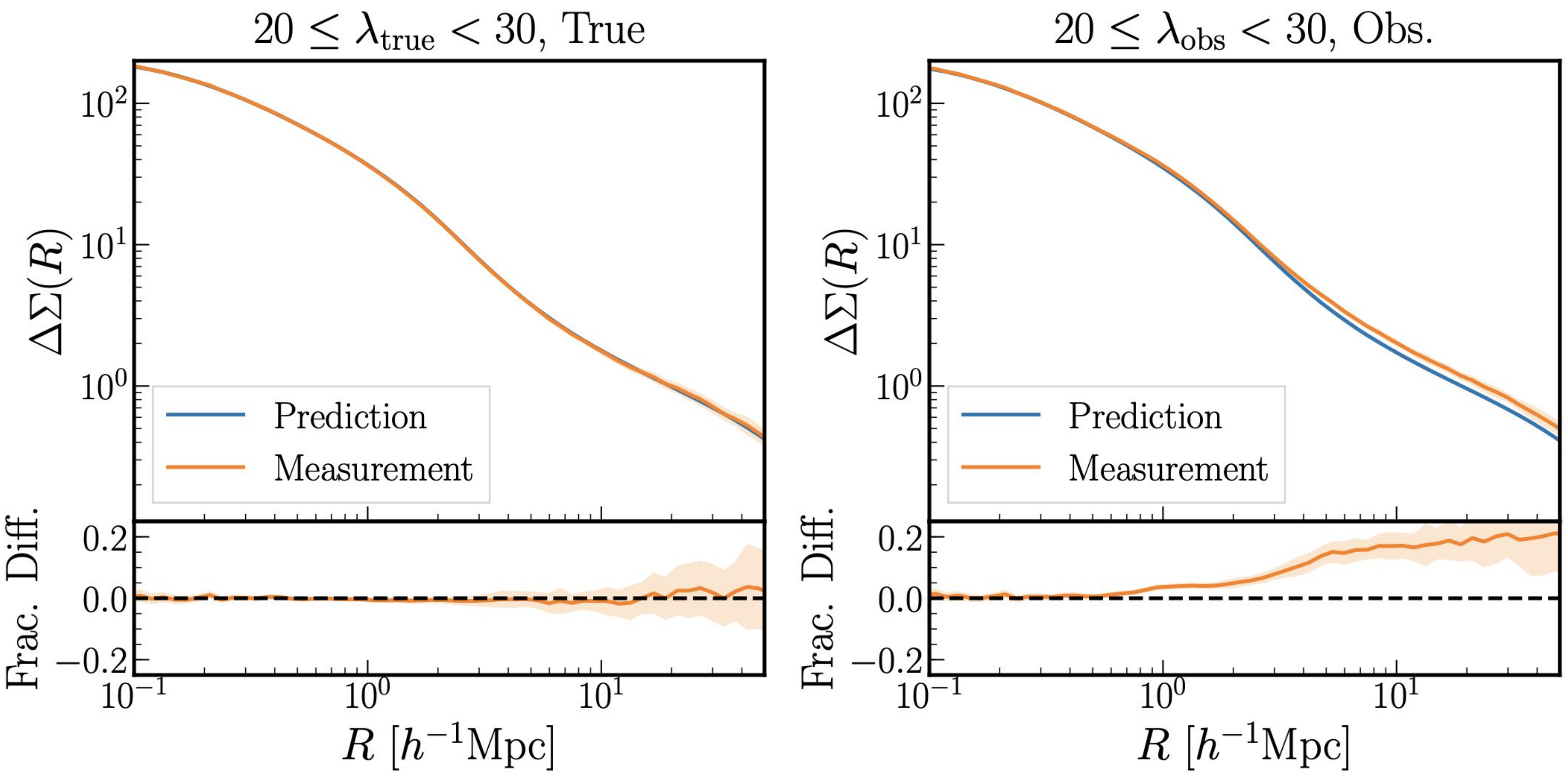
Projection Effects: Impact on Richnesses

Projection tail



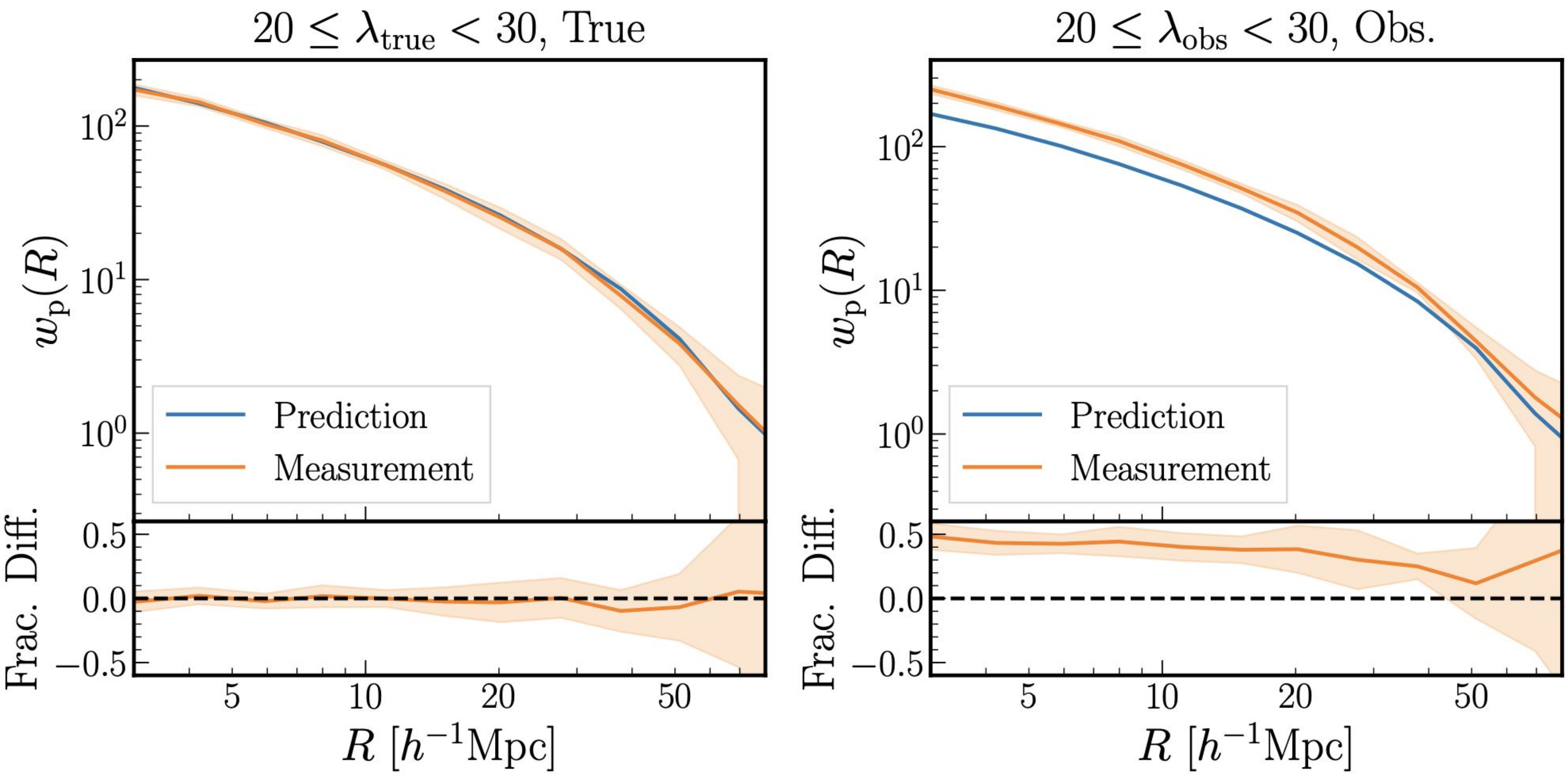
Sunayama, YP, Takada et al. (2020)

Unexpected Large-Scale Boosts



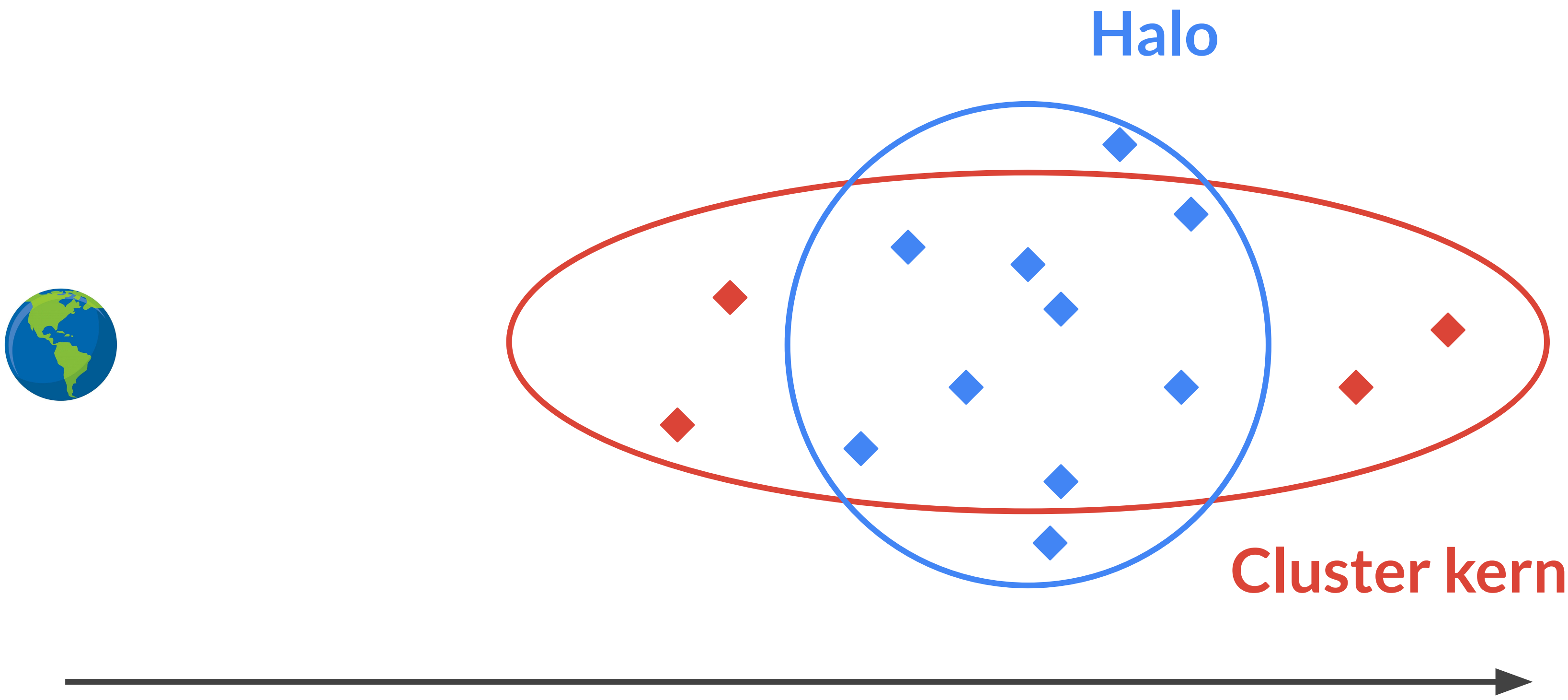
Observed clusters show a clear large-scale boost in lensing!

Unexpected Large-Scale Boosts

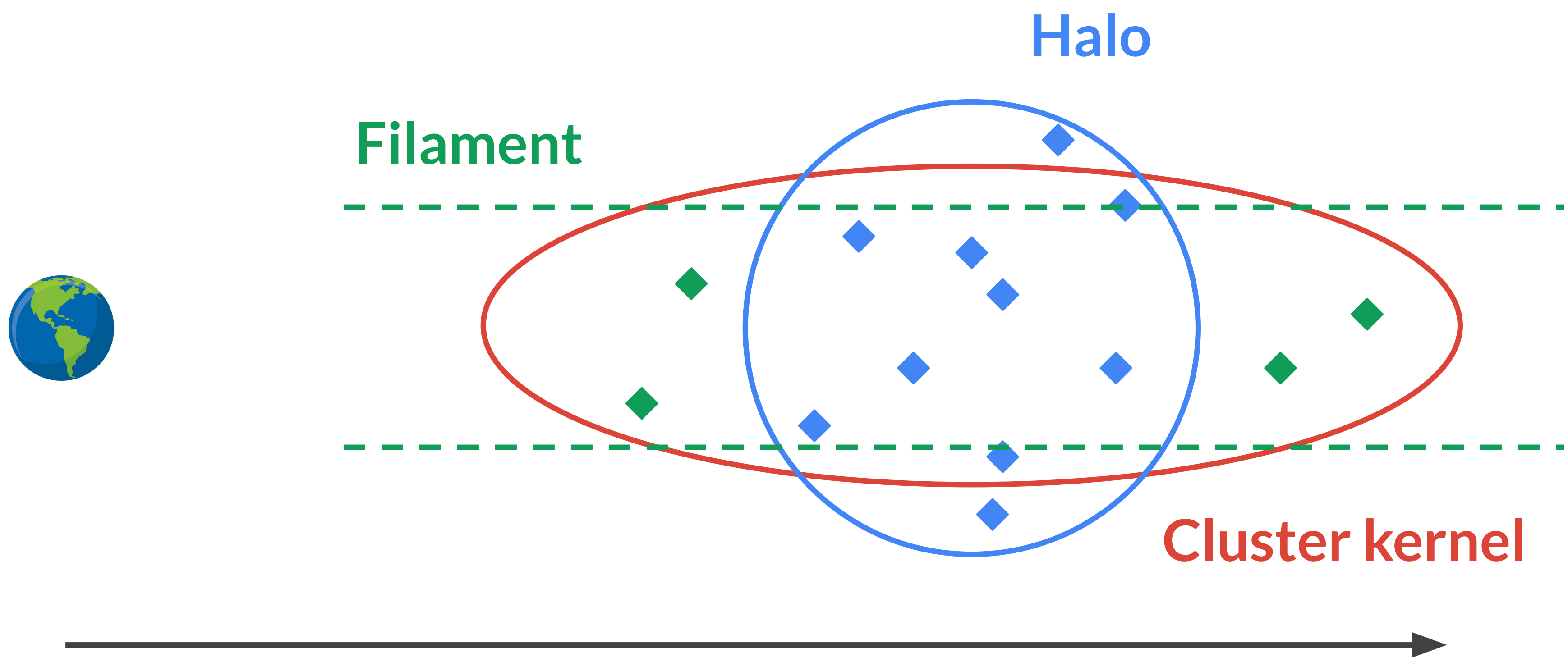


And consistent boosts are also found in clustering!

Interpreting Projection Effects



Interpreting Projection Effects

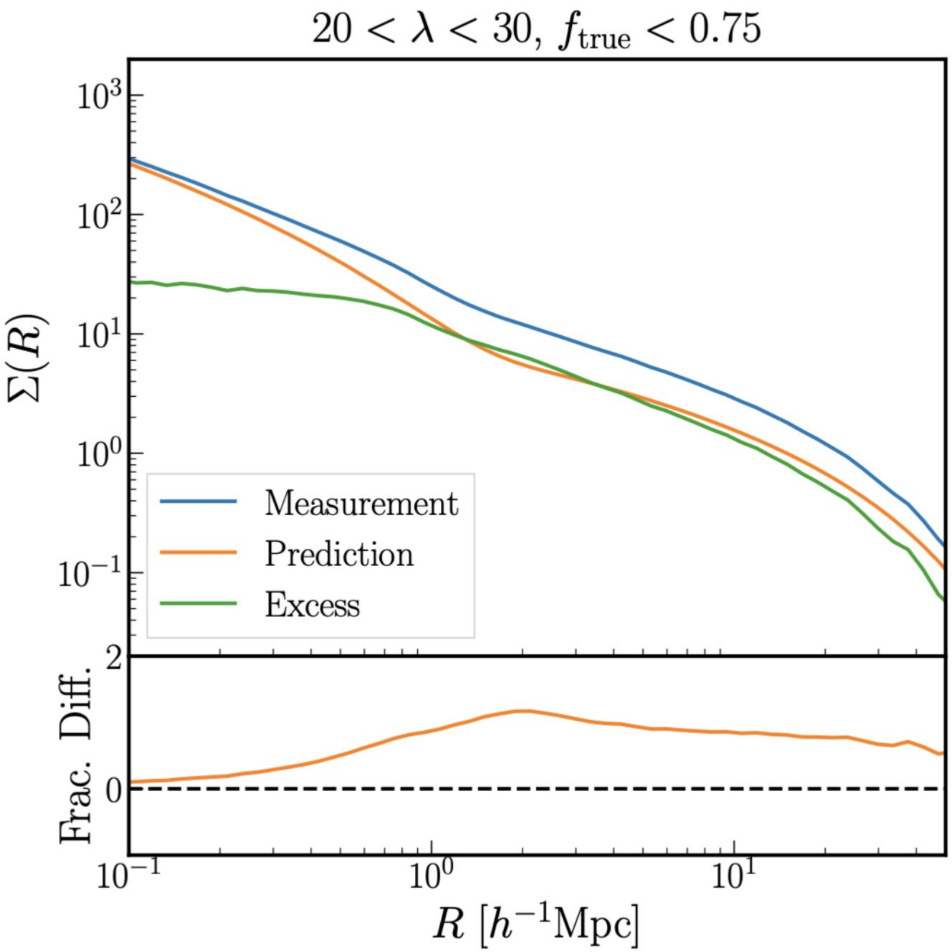


Cluster kernels naturally prefer aligned filaments
that modify lensing/clustering signals

Now to Cosmology

- **Cluster Cosmology Observables**
    - Cluster abundances
    - Cluster lensing
    - Cluster clustering
- **Modeling Ingredients**
    - Halo model predictions from the `dark emulator`
    - Mass-Observable Relation
    - Systematic effects (photo-z, boost factors, miscentering, …)
    - *Projection effects*
- **Forward-model all observables for multiple richness bins**

Modeling Projection Effects for Cosmology



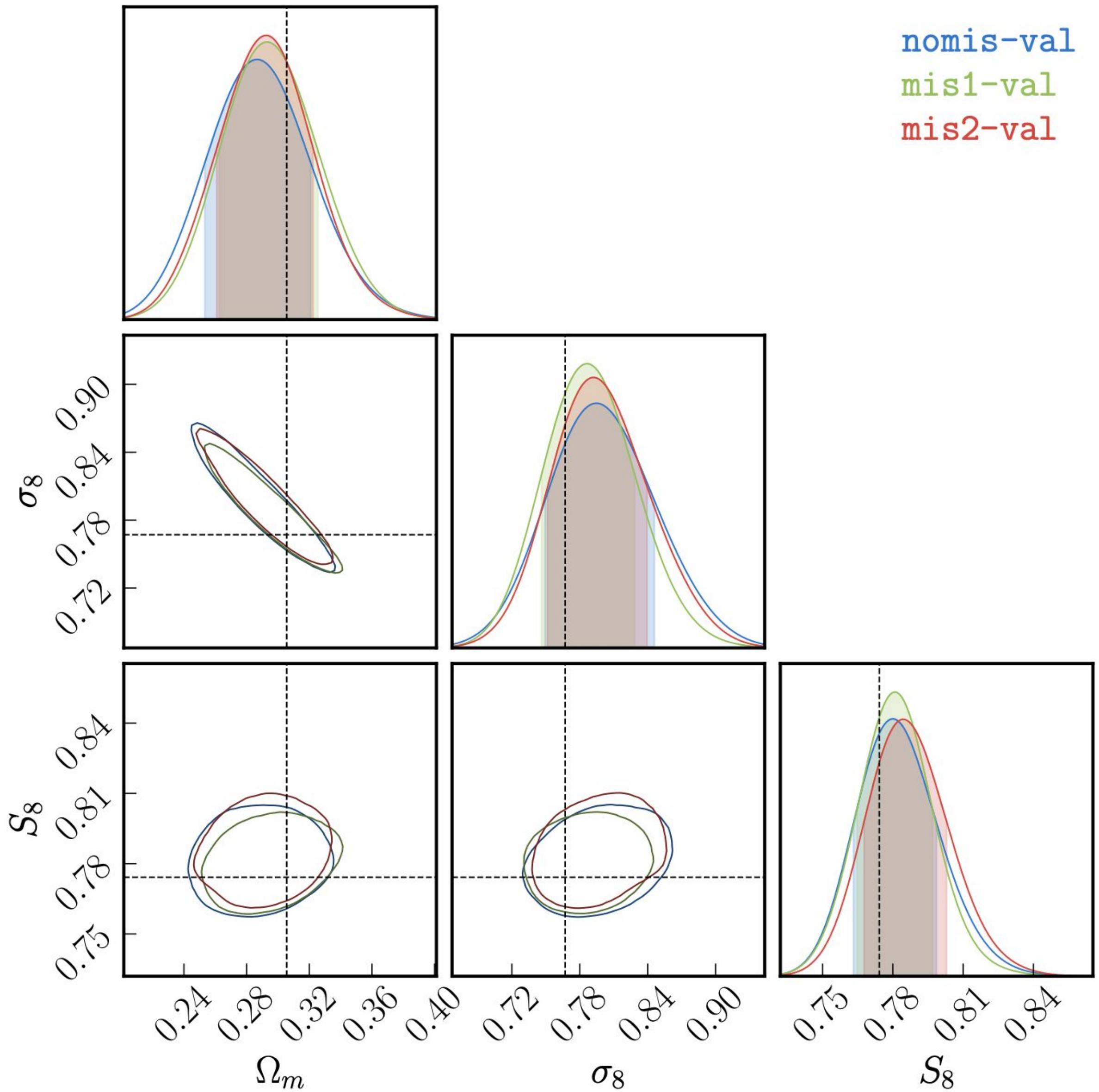
Model the excess mass as a multiplicative factor

$$A(R) = \begin{cases} A_0 (R/R_0) & \text{for } R \leq R_0, \\ A_0 - c \ln(R/R_0) & \text{for } R > R_0. \end{cases}$$

And treat it as effective biases

$$\begin{aligned} \Sigma^{\text{proj}}(R) &= A(R)\Sigma^{\text{iso}}(R), \\ w_{\text{p}}^{\text{proj}}(R) &= A^2(R) w_{\text{p}}^{\text{iso}}(R). \end{aligned}$$

Validating the Model



Application to SDSS RM

- **Data Set**
  - Based on the Sloan Digital Sky Survey (SDSS) DR8 photometry
  - Covers ~ 10,000 deg^2 with ~ 8,000 RM clusters
  - Additionally ~ 39 million background galaxy shapes

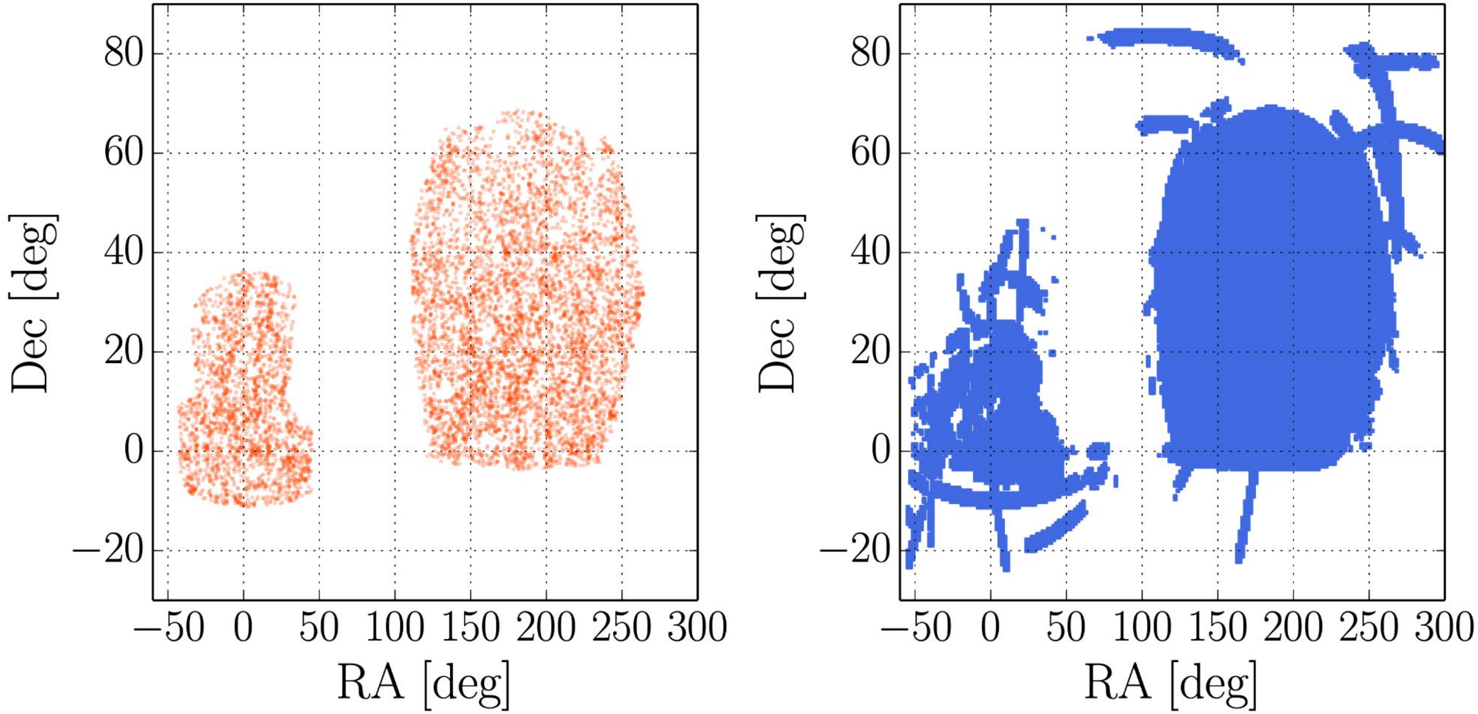
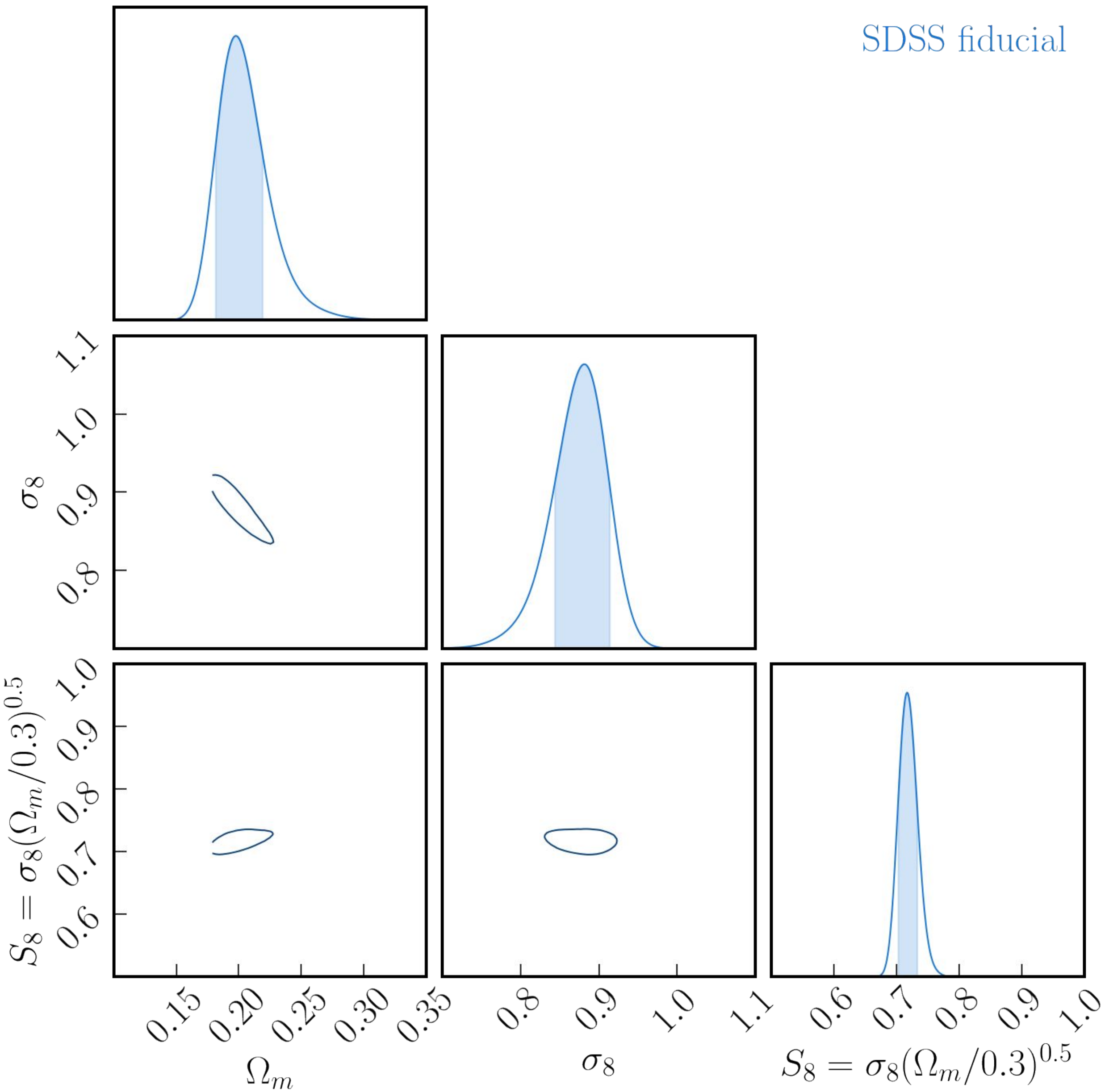


Figure from Murata et al. (2017)

Fiducial Results from SDSS RM



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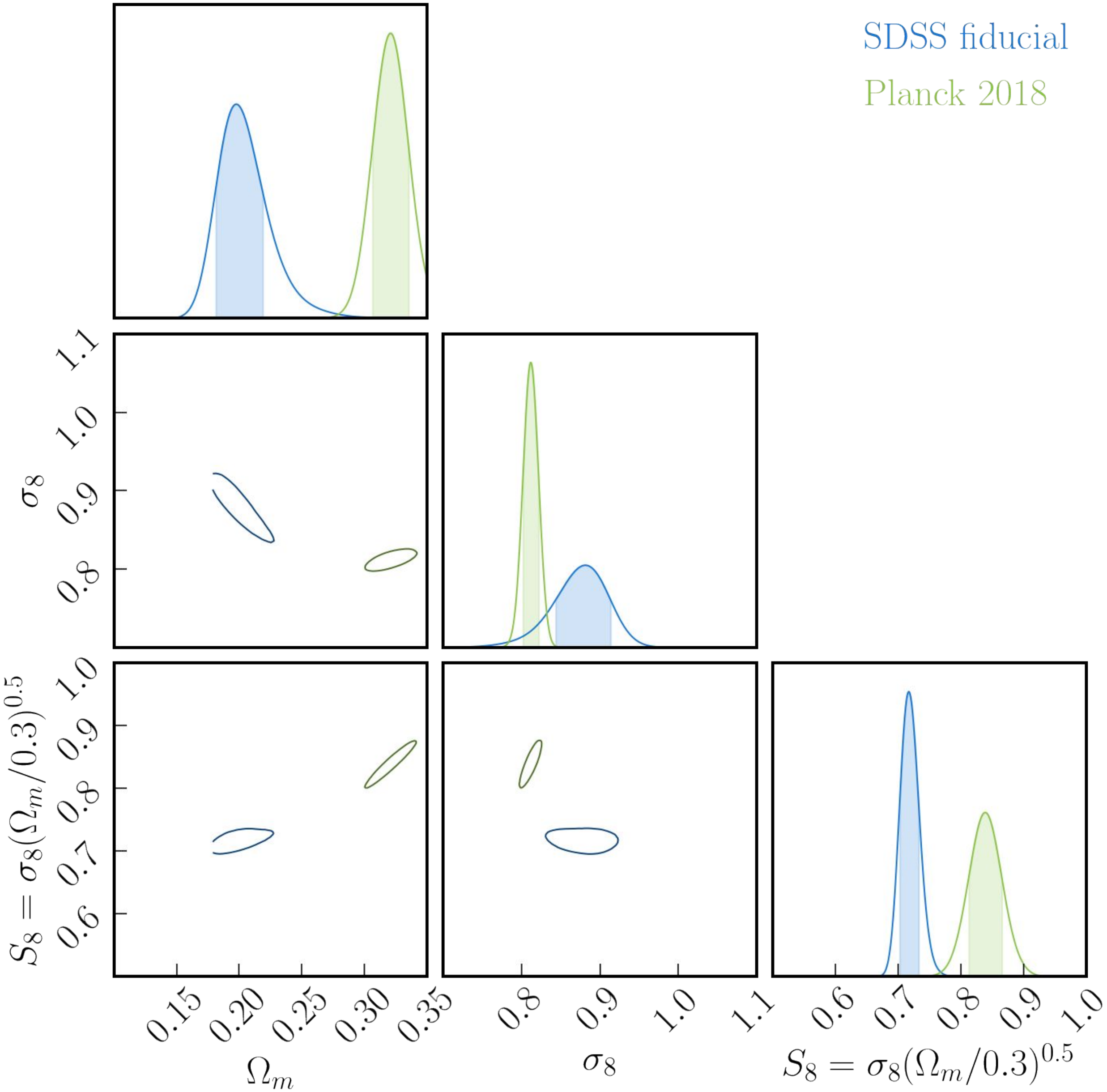

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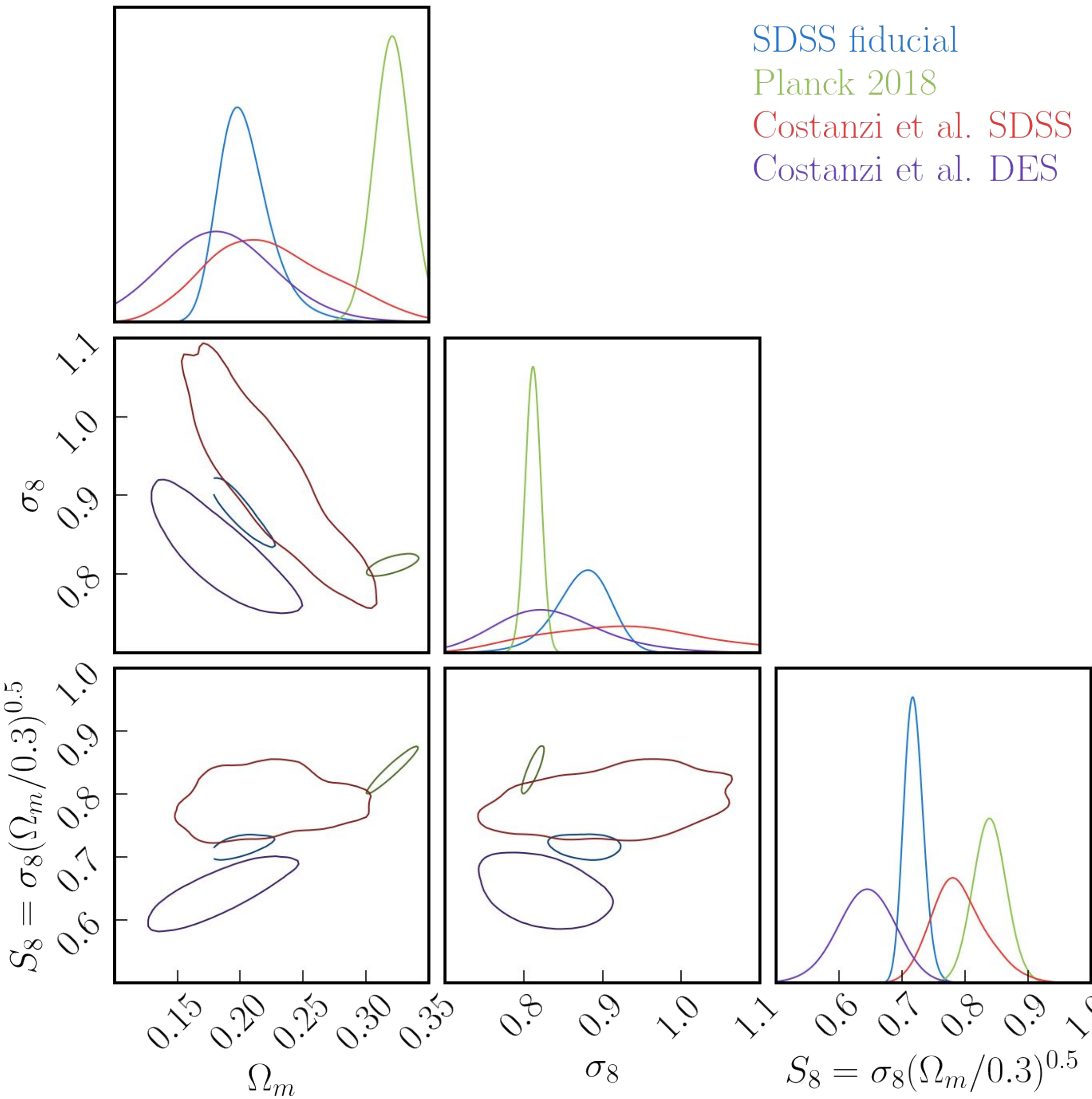


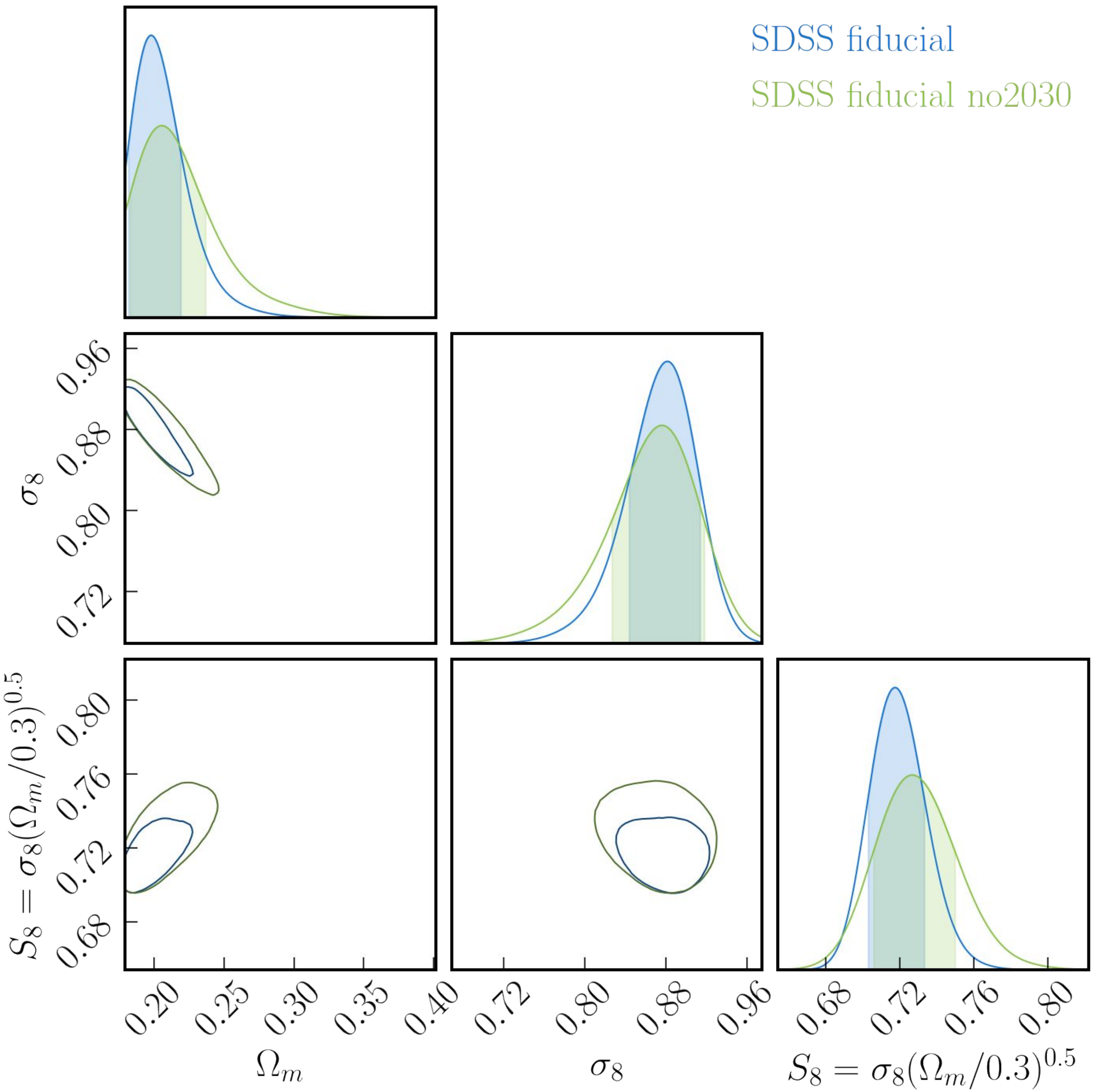
Beware!

A Posteriori Results Beyond This Point

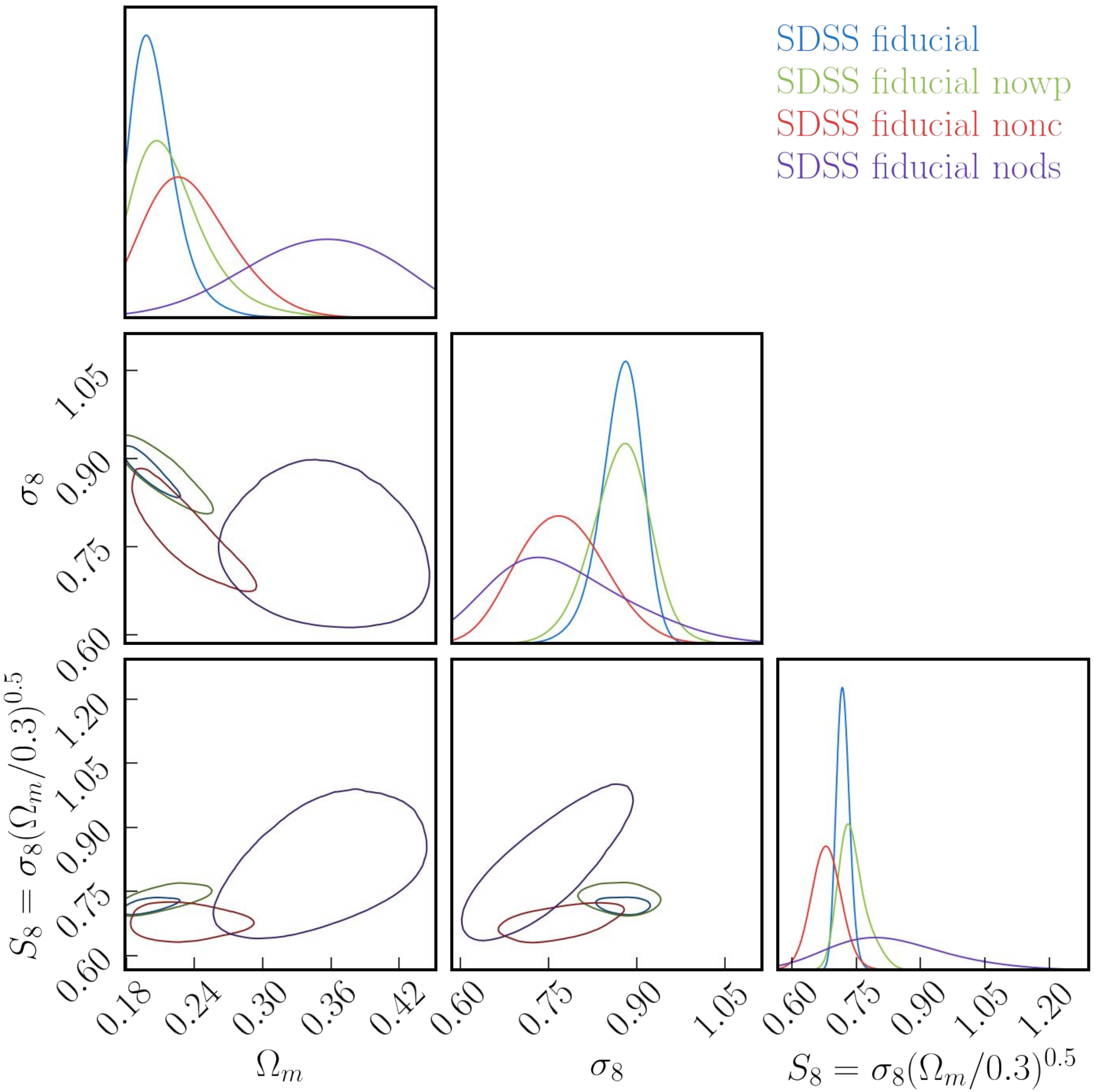
Confirmation Bias Sightings Reported

You Have Been Warned

Post-Unblinding Tests



Post-Unblinding Tests



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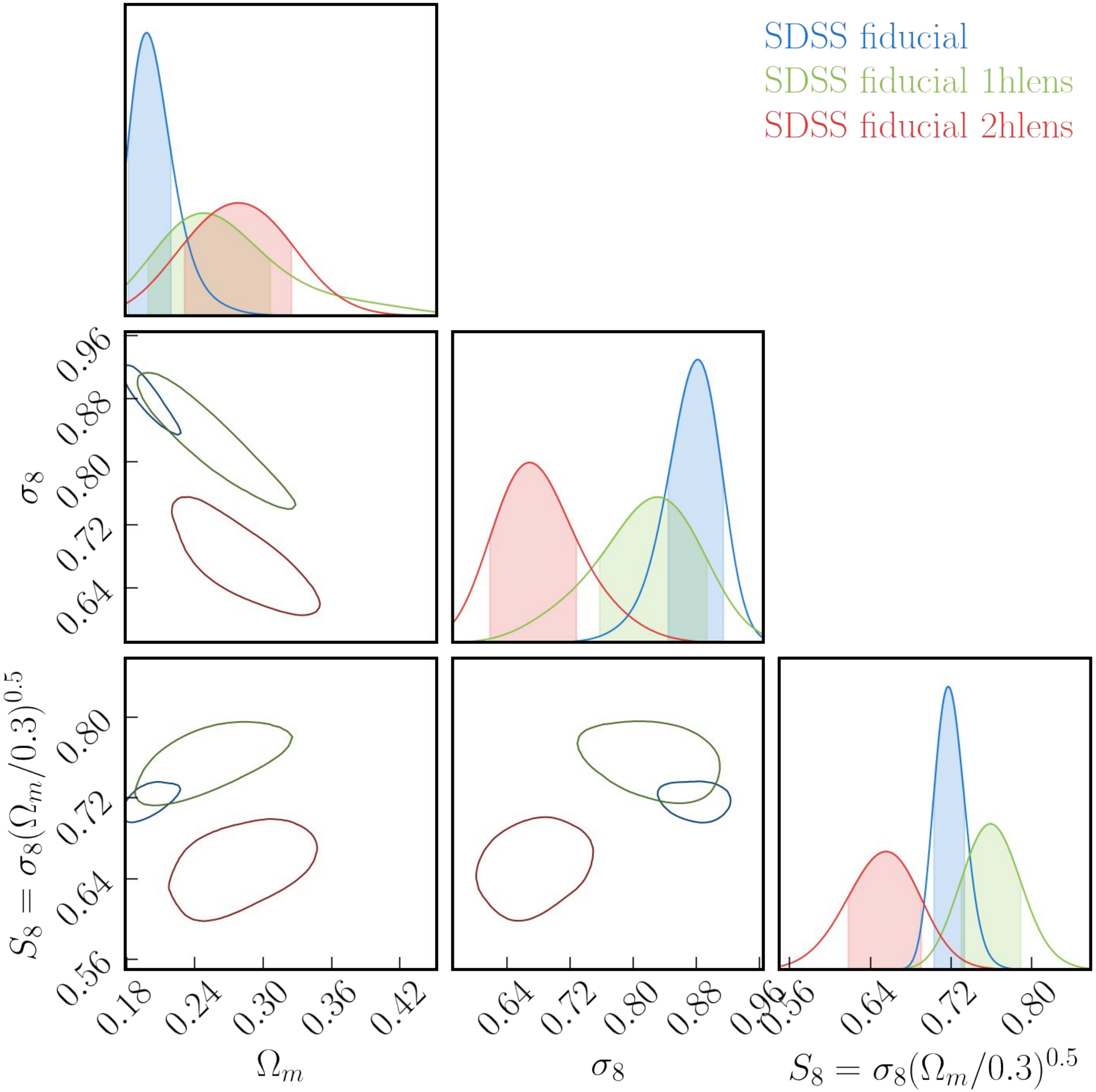

So, What Now?

- **From simulations to real data**
  - Pipeline was fine on the validation challenge, but on real data shows confusing results
  - Several important differences between simulations and real data
    - Assumed vs. real galaxy-halo connection
    - Lensing via true matter distributions vs. via galaxy shapes
    - Mismodeling in known observational systematics
    - **New physics?!**
- **Coincidences (?)**
  - Both our results and results from DES are in consistent disagreement against "standard" cosmology results, e.g., Planck
  - If more than a coincidence, this points at problems affecting optical clusters across different data sets and analyses

So, then What Next?

- **Near term**
  - Follow-up studies on the cosmology results
  - First HSC-SSP cluster cosmology
  - DES Y3 cluster cosmology
- **Longer term**
  - Multi-wavelength cluster cosmology: optical + microwave + X-ray
  - Enabled by upcoming cosmological surveys
    - Rubin LSST / PFS / DESI / Roman
    - Simons Observatory / CMB-S4
    - eROSITA
  - Allows for *cross*-calibration, rather than *self*-calibration, of systematics